

# **PERFORMANCE OF DECADE MODULE #1 (DM1) AND THE STATUS OF THE DECADE MACHINE\***

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## **Abstract**

DECADE is a very high power generator that will be built at Arnold Engineering Development Center in Tullahoma, Tennessee by the Defense Nuclear Agency. The full facility consists of 16 modules. A full power module (DM1) has been built and tested to verify the DECADE design at Physics International. The module consists of a 570 kJ Marx generator that pulse charges a water transfer capacitor. The transfer capacitor discharges into a water output line through an array of 6 parallel triggered gas switches. The water output line then pulse charges the inductive store/opening switch pulse compression stage. When the opening switch opens, the inductive store discharges into an electron beam bremsstrahlung diode load.

The initial testing of the DM1 module has been completed. The electrical design of the module will be presented, including circuit modeling results. The test data from the module will be compared to the modeling results. The concept for combining 16 modules that are similar to DM1 into the DECADE generator will be presented. Test data from DM1, such as the modular timing jitter, that supports the DECADE system design will also be presented.

## **Introduction**

The DECADE facility will be the first high power x-ray simulator in the US to be built using inductive store/opening switch (IS/OS) technology for the final phase of pulse compression. The advantage of using IS/OS technology is that the energy is stored magnetically at high density near the load providing for high power, short pulse discharge once the opening switch opens. The plasma opening switch (POS) has been used for pulse compression and power amplification in a variety of inductive energy storage systems with conduction times ranging from tens of nanoseconds to over one microsecond.<sup>(1-7)</sup> The use of IS/OS technology rather than the conventional capacitive storage technology becomes critical for large ( $> 50$  TW), short pulse (20 ns) electron beam (bremsstrahlung x-ray) generators.

The DECADE machine will use one stage of capacitive pulse compression to charge the final IS/OS stage. This initial stage of pulse compression reduces the opening switch conduction time from 1.5  $\mu$ sec (if driven directly by the Marx generator) to 300 ns. The motivation for designing the machine for shorter conduction time is two fold; the opened impedance of the opening switch is higher at shorter conduction times and the jitter in the conduction time is less. The desire for low jitter in the conduction time comes from the requirement to synchronize multiple modules in larger systems and the fact that the opening switch is not command triggered.

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The modular approach for DECADE was chosen to allow full power module verification tests prior to completing the full 16 module DECADE machine. The choice of 16 modules was based on the requirement to minimize the risk of scaling up the power per opening switch beyond what had been demonstrated previously. A factor of two increase in the power per opening switch as was previously demonstrated on the DECADE prototype module<sup>(8, 9)</sup> (DPM1) was chosen as the design point for the DECADE module.

The system design for DECADE up to the plasma opening switch (POS) has been completed and a full power module that is electrically identical and mechanically similar to a DECADE module has been built and tested for over 1500 shots. The pulsed power driver up to the POS has met all the requirements (peak current, charge time, reliability and maintainability) for building the DECADE facility. The work in progress is to complete the scale-up of the POS in the constrained geometric configuration as required for the 16 module system.

In the remainder of this paper, we will first review the electrical and mechanical descriptions of each component followed by a comparison of the circuit model with a shot from DM1. The last section will review the mechanical description of the 16 module DECADE system and the relevant x-ray and electrical measurements that confirm the ability to combine the output from multiple modules.

## DECADE Module (DM1) Description

A side view of the DECADE test module is shown in Figure 1. The principle components are the Marx generator, the transfer capacitor (TC), the triggered output switches, the water output line (OL), the vacuum insulator, the magnetically insulated transmission line (MITL) that serves as the inductive store, the plasma opening switch (POS) and the electron beam/bremsstrahlung diode load. Also, shown in this figure is a sketch of the power or energy transfer from the Marx to the load. The discharge sequence begins by first command triggering the Marx generator, this results in pulse charging the transfer capacitor (TC). Output switches are then command triggered and the pulse is transported down the output line prior to charging the inductive store/POS stage in 250 ns. The final event is the opening of the POS, this discharges the inductive store as a current charged pulse forming line into the diode load. The three trigger systems for DECADE; Marx, TC output switches, and POS plasma sources are designed and built by PSI/TITAN.

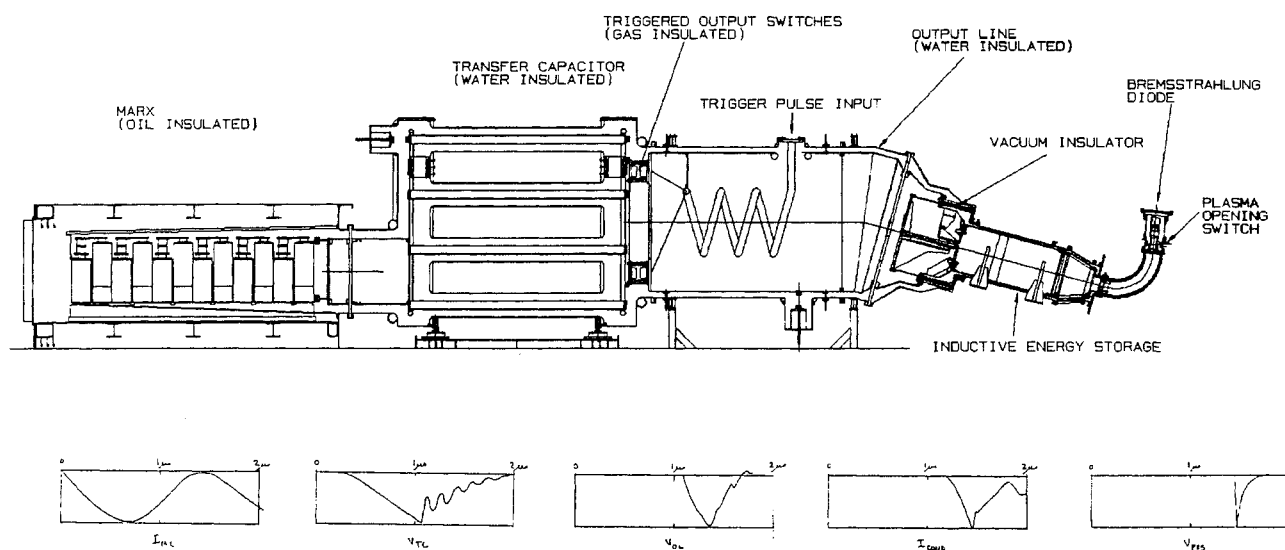


Figure 1. Side view of the DECADE test module.

The Marx generator is shown in Figure 2. The Marx contains six parallel submarxes as shown in Figure 2(a). Each submarx consists of 6 plus and minus high voltage stages separated by an SF<sub>6</sub> insulated gas switch as shown in Figure 2(b). Each of the submarxes can easily be removed as a plug-in unit for repair or maintenance as shown in Figure 2(c).

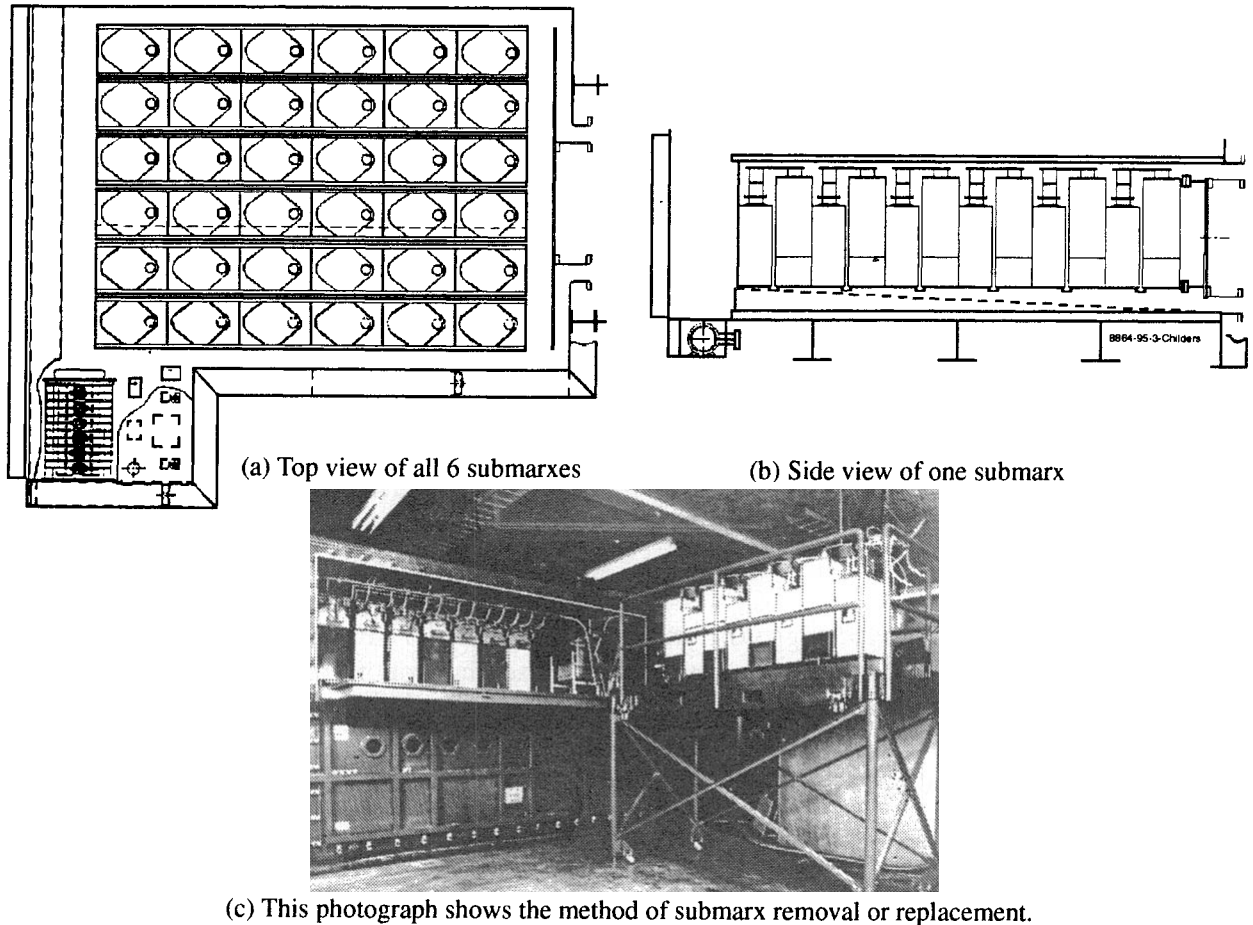
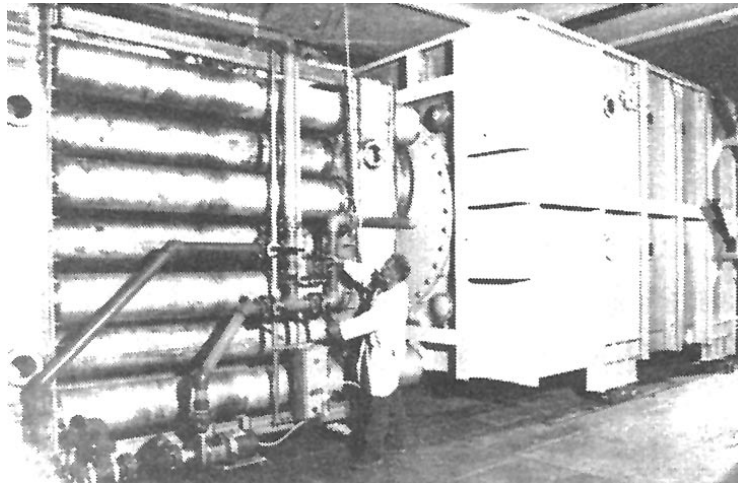


Figure 2. Mechanical description of the DECADE Marx generator

Each of the six stages in a submarx is charged to  $\pm 85$  kV. The twelve capacitors in a submarx are Aerovox 2.2  $\mu\text{F}$ , 100 kV rating. At  $\pm 85$  kV the submarx contains 95 kJ for a total stored energy in the DM1 Marx of 570 kJ. Once the Marx is triggered, the erected capacitance is 1.1  $\mu\text{F}$  and the voltage is 1.02 MV. Three of the six switches of each submarx is command triggered. The trigger source is a 550 kV, 13 nF minimarx.

The next stage of capacitive storage pulse compression is a water transfer capacitor (TC) and an array of 6 high voltage triggered gas switches. The TC is shown in Figure 3. The TC is 32 water insulated coaxial stainless steel tubes. This capacitor is 75 ns long and is 400 nF. The design point of the capacitor, taking into consideration the area of 16 of the capacitors (DECADE design), is 86% of JCM criteria. The water is constantly circulated through the deionization and deaeration bed.

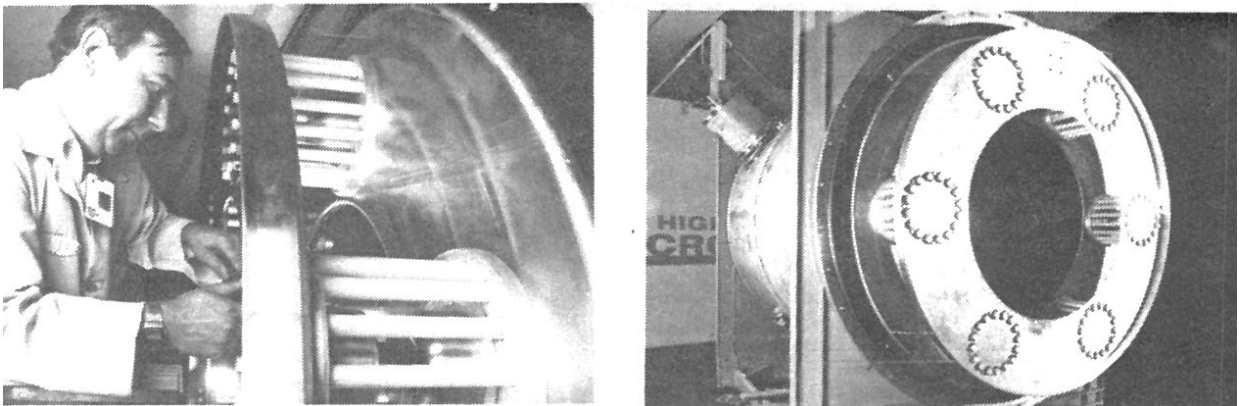
The DECADE module has a total of 8 diverters, six on the TC and two on the output line. These diverters are designed to remove the waste energy (about 320 kJ out of 570 kJ stored) as soon as possible after the forward pulse is completed. This careful removal of waste energy results in a reliable low maintenance machine by minimizing the coulomb transfer in the gas switches and preventing late in time arcing in the water sections. The majority of mechanical damage in large high power machines is due to the resonant ringing of the waste energy in the system.



**Figure 3. Photograph of the Transfer Capacitor.**

The transfer capacitor is protected from damage by three diverters at each end of the TC. The water gap on these diverters is adjusted to breakdown just after the first zero crossing in the voltage pulse. These diverters include copper sulfate resistors that provide the damping action. Each diverter is designed to absorb up to 270 kJ.

The TC is discharged by command triggering an array of six parallel  $\text{SF}_6$  insulated gas switches. The switches, shown in Figure 4, are mounted on a single ring to facilitate routine maintenance by replacing all the switches as a unit. The peak voltage on these switches is typically 1.4 MV and they carry a total current of 1.6 MA. The shot to shot timing jitter is less than 5 ns. Adjusting the timing between multiple DECADE modules can be accomplished by changing the timing of the trigger pulse to these output switches.



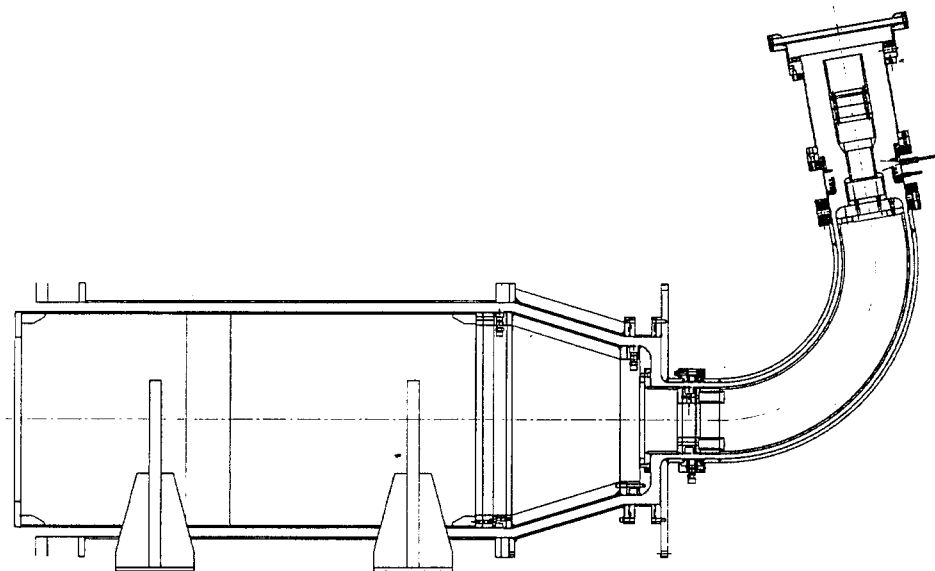
**Figure 4. There are six switches in parallel that are used to discharge the Transfer Capacitor.**

The water insulated output line (OL) is pulse charged by the TC. This is not an active (switched) stage of pulse compression. The OL isolates the output switch inductance from the inductive store inductance and thus reduces the time to peak current and thus the POS conduction time by 40%. This single coaxial water-line is  $0.5 \Omega$  impedance and is 100 ns long. The electrical trigger for the output switches is fed along an inductive isolator inside the cathode of the OL.

At the end of the OL there is a transition from the water to oil. There is a short section of oil insulated transmission line between the OL and the vacuum insulator. This oil section facilitates uniform field grading along the vacuum insulator tube stack.

The vacuum insulator is a sixteen insulator/gradient ring stacked configuration. The total insulator stack height is 35 cm. The tube stack is conservatively designed at 60% JCM ( $F t_{\text{eff}}^{1/6} A^{1/10} = 175$ ). The vacuum insulator is designed so there is no vacuum flashover during a shot. This overall conservative design results in over 25 operational shots before cleaning of the insulator surface. The insulators are a composite material with the bulk being polyurethane for mechanical strength and the vacuum surface being Limitrak<sup>(10)</sup> for dendrite resistance. If there is damage to the vacuum surface the insulator can be repaired in place.

The inductive store/opening switch final pulse compression stage is shown in Figure 5. In addition to the vacuum MITL hardware shown, the inductive storage part of the circuit includes the inductance of the tube oil feed and the tube section. The vacuum MITL is 3.5 m from the vacuum tube to the POS. The MITL has a  $5.0 \Omega$  straight section followed by a taper down to  $7.5 \Omega$  at smaller diameter ( $\approx 10$ -inch-diameter anode). The  $7.5 \Omega$  MITL has a bend as shown. This bend is required for the combination of multiple modules into the DECADE system as seen later in Figure 10. All MITL hardware is stainless steel. There are several current monitors (four azimuthal B-dots located in a groove) located along the anode electrode. The typical vacuum pressure prior to a shot was  $5 - 7 \times 10^{-5}$  torr. The pumping system is a mechanical roughing pump, two cryogenic pumps and a liquid nitrogen cooled coil near the POS.



**Figure 5. Mechanical description of the Inductive Energy Store Plasma Opening Switch and Bremsstrahlung Diode Load.**

The POS is shown in Figure 5 immediately after the bend in the MITL. The plasma sources are twelve 0.25-inch-diameter coaxial cable guns. The plasma guns are fired a few microseconds before triggering the Marx generators. The plasma fill in the anode-cathode gap of the POS region of the MITL serves as the conducting medium until the ions in the plasma are depleted and the POS increases in impedance and begins to open.

The diode load also shown in Figure 5 is a 5-inch-diameter hollow cathode cylinder with a 0.75 inch gap to a tantalum anode foil. The tantalum foil serves as a high atomic number bremsstrahlung converter producing x-rays. The tantalum thickness is chosen to be approximately one fifth of the range of the average electron energy for optimum radiation production efficiency. There is a one inch thick polyethylene beam stop to prevent high energy electrons from exiting the machine.

## Circuit Model and Output Performance

A circuit model has been developed over the last few years as a design tool for the DECADE system. Most of the circuit elements are modeled as transmission line segments. The computer code then simulates circuit performance by keeping track of transmission and reflection at the transmission line segment interfaces. The code runs quickly on an IBM-386 (or higher) PC, since no differential equations are solved. The circuit model for DM1 is shown in Figure 6. The model has been developed to attain excellent agreement with electrical performance of all components up to the conduction current into the POS. Due to the presence of plasma and electron beam between the POS and the diode there are presently no reliable electrical diagnostics to allow quantitative calibration of the model down stream of the POS.

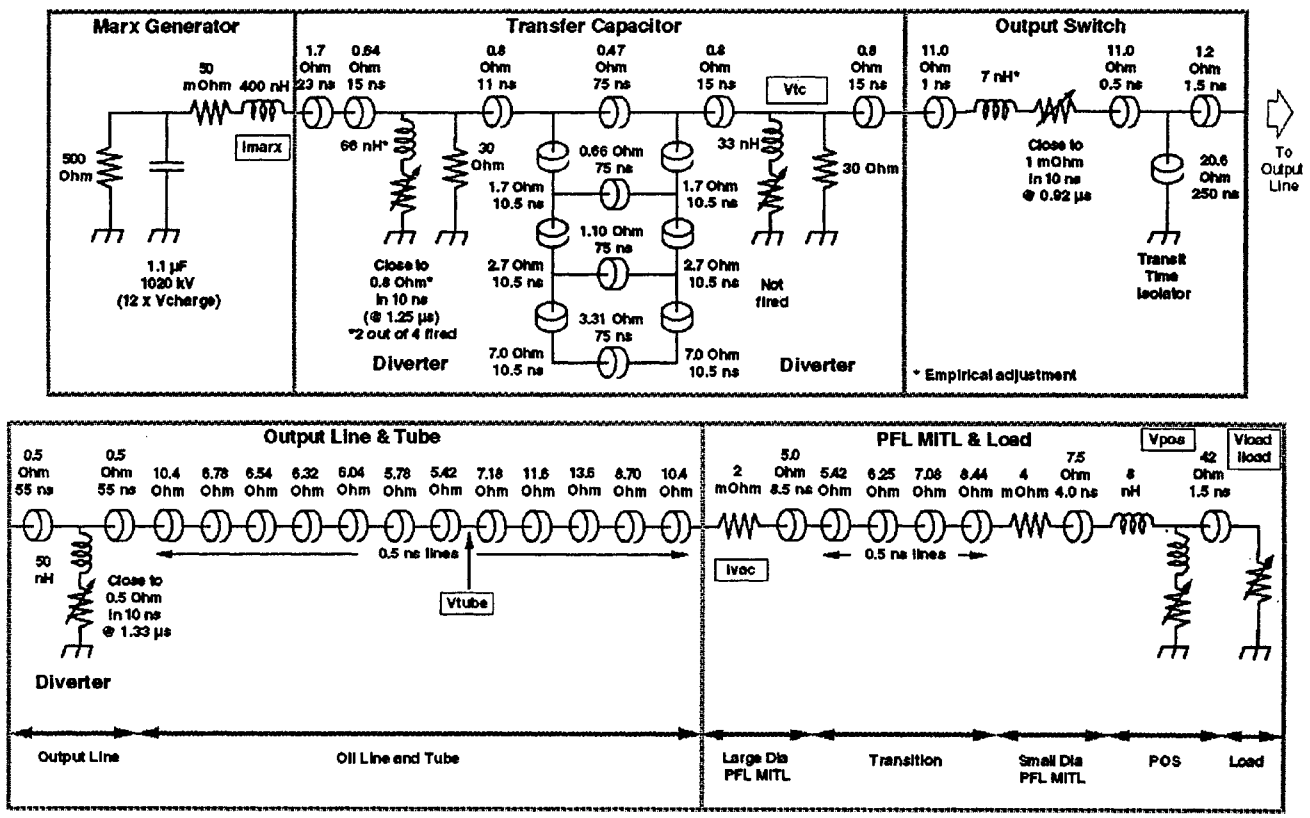
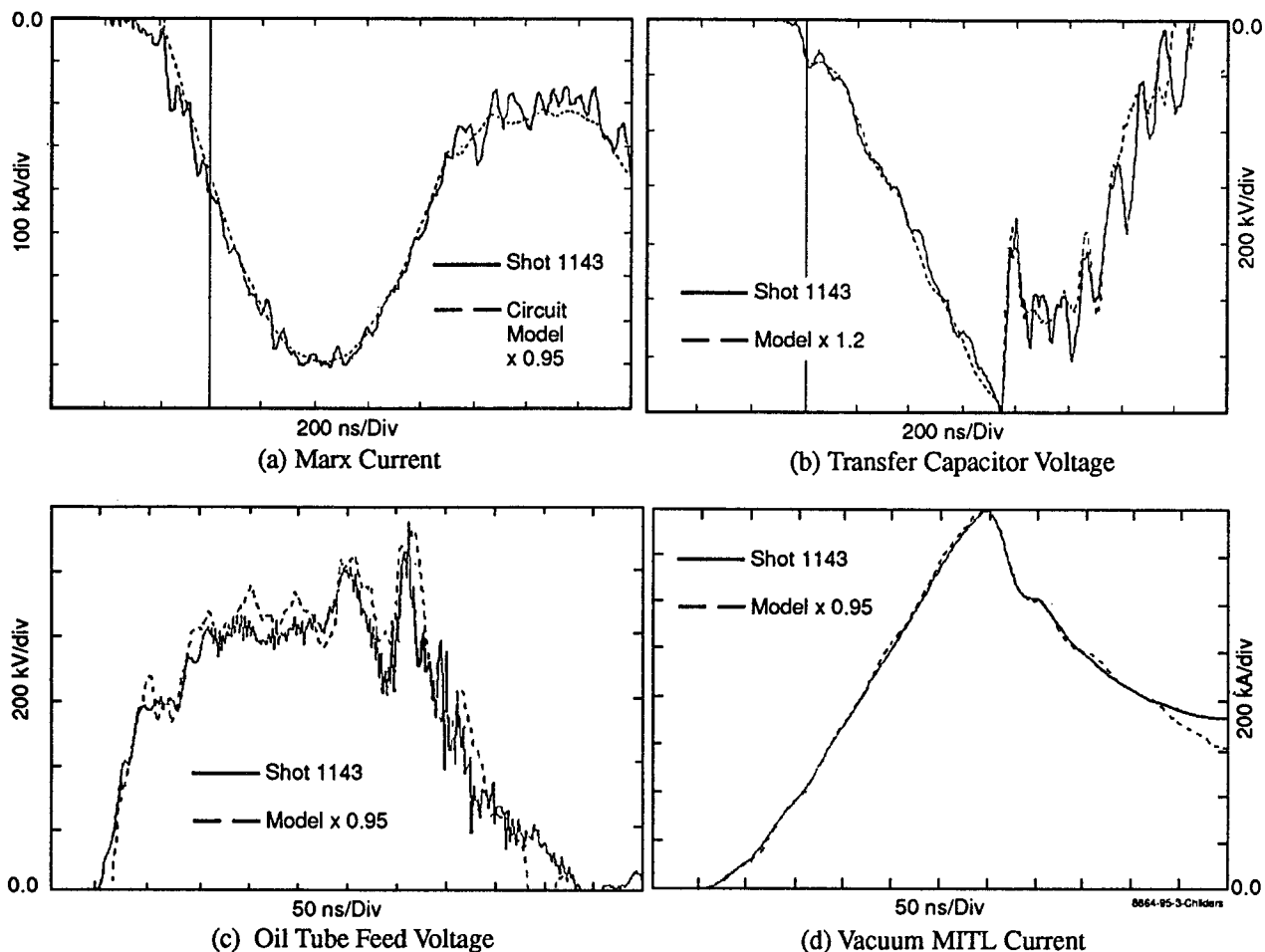


Figure 6. Computer circuit model of DM1.

The principal electrical diagnostics along the machine are Marx current monitors (current viewing resistors on each submarx), capacitive voltage monitor on the TC, capacitive voltage monitor in the oil upstream of the tube, current monitors in oil and vacuum (B-dots) at the tube and in the anode upstream of the POS. The current monitors and the tube voltage monitor are calibrated to about  $\pm 5\%$ . The voltage monitor on the TC has not been carefully calibrated.

The measured waveforms along the machine are compared to the model calculations for shot 1143 as shown in Figure 7. The model calculations agree within experimental error for the well calibrated monitors and the shape of the voltage on the TC agrees with the measurement.





**Figure 7. Electrical Measurements from DM1 Shot 1143 agree within 5% with the circuit model results (Marx to the POS.).**

The voltage produced by the opening action of the POS can be “measured” using the voltage measured at the tube, the current measured in the MITL and the known impedance and length of the transmission line between the monitor and the POS location. A comparison of the “measured” voltage at the POS with the model calculations is shown in Figure 8(a). The agreement between the model calculations and the measured waveforms is attained by adjusting the assumed profiles for the diode and POS impedances. The final assumed profiles that achieved optimum agreement in both shape and amplitude are shown in Figure 8(b).

In addition to the electrical measurements discussed above, there are also x-ray radiation measurements including a filtered Si PIN that provides a measurement of the x-ray power pulse shape. An example of the measured x-ray power pulse shape from shot 1143 is shown in Figure 8(c). The timing jitter of this radiated power is critical to the analysis of the predicted performance of a multiple module system as discussed in the next section.

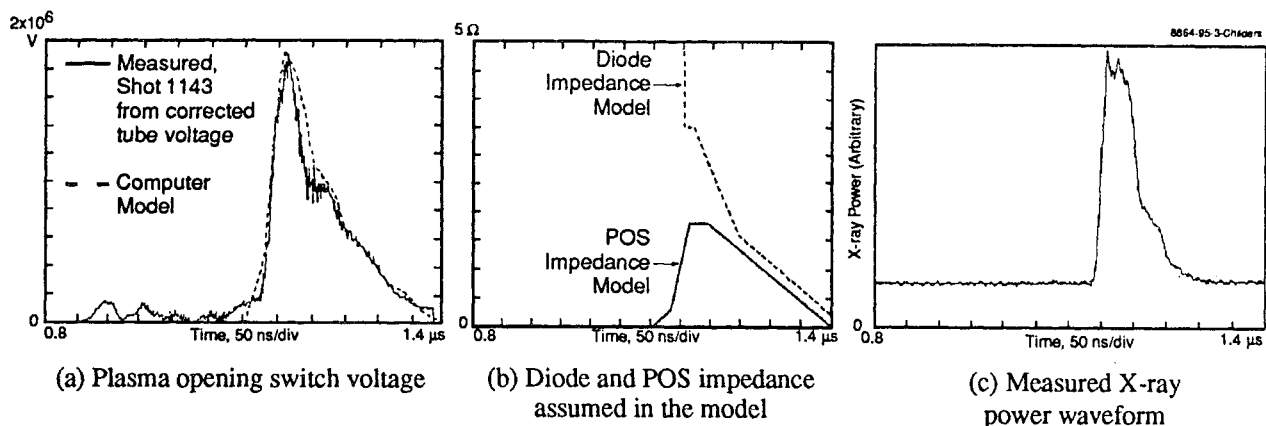


Figure 8. POS and load measured and assumed waveforms.

## DECADE System Design

The planned DECADE machine is shown in Figure 9. This machine consists of 16 electrically independent modules similar to the DM1 module. Each of the 4 large Marx tanks contains 4 separate Marx modules. Each of the quads (large Marx tank plus 4 TCs and OLs) is mounted on tracks and is designed to move back to facilitate tube, MITL, and output switch maintenance. A more detailed three dimensional isometric CAD drawing of DECADE from the OL forward is shown in Figure 10. This drawing shows the tapered water

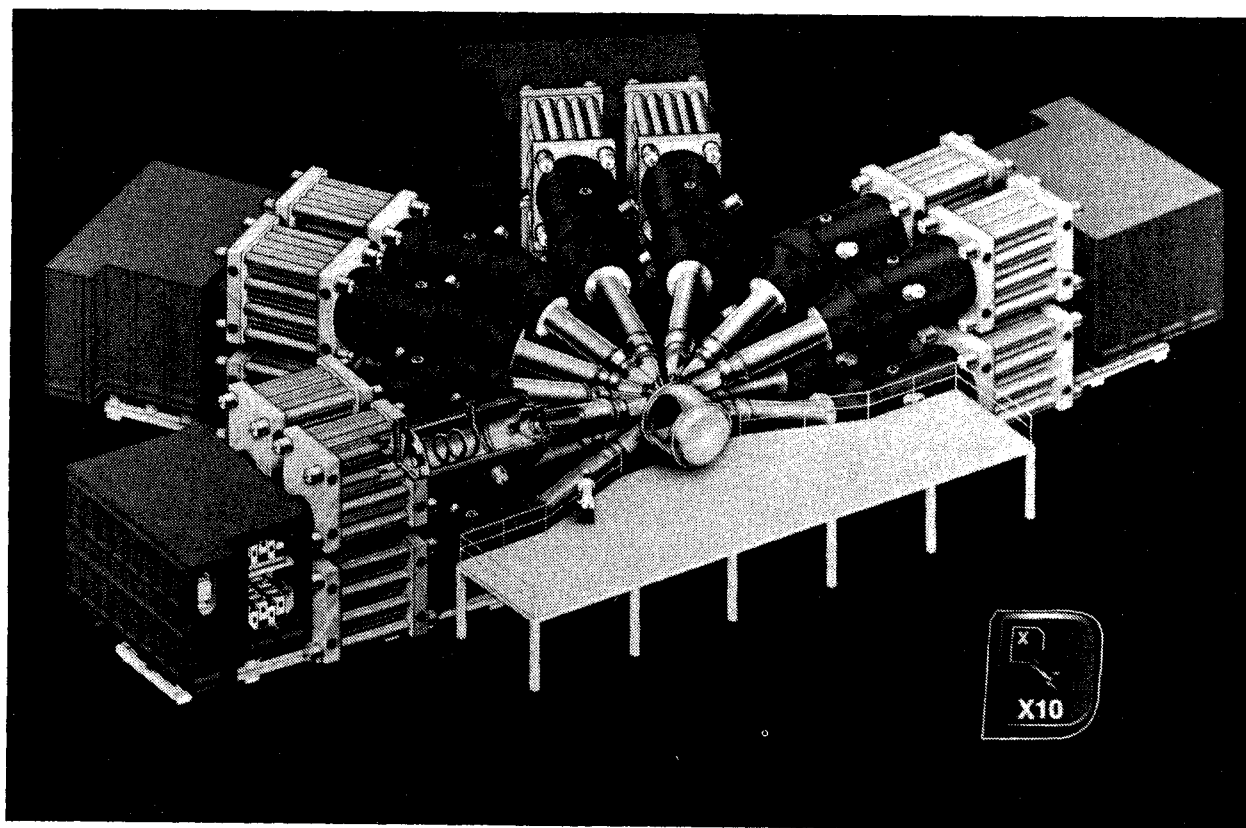
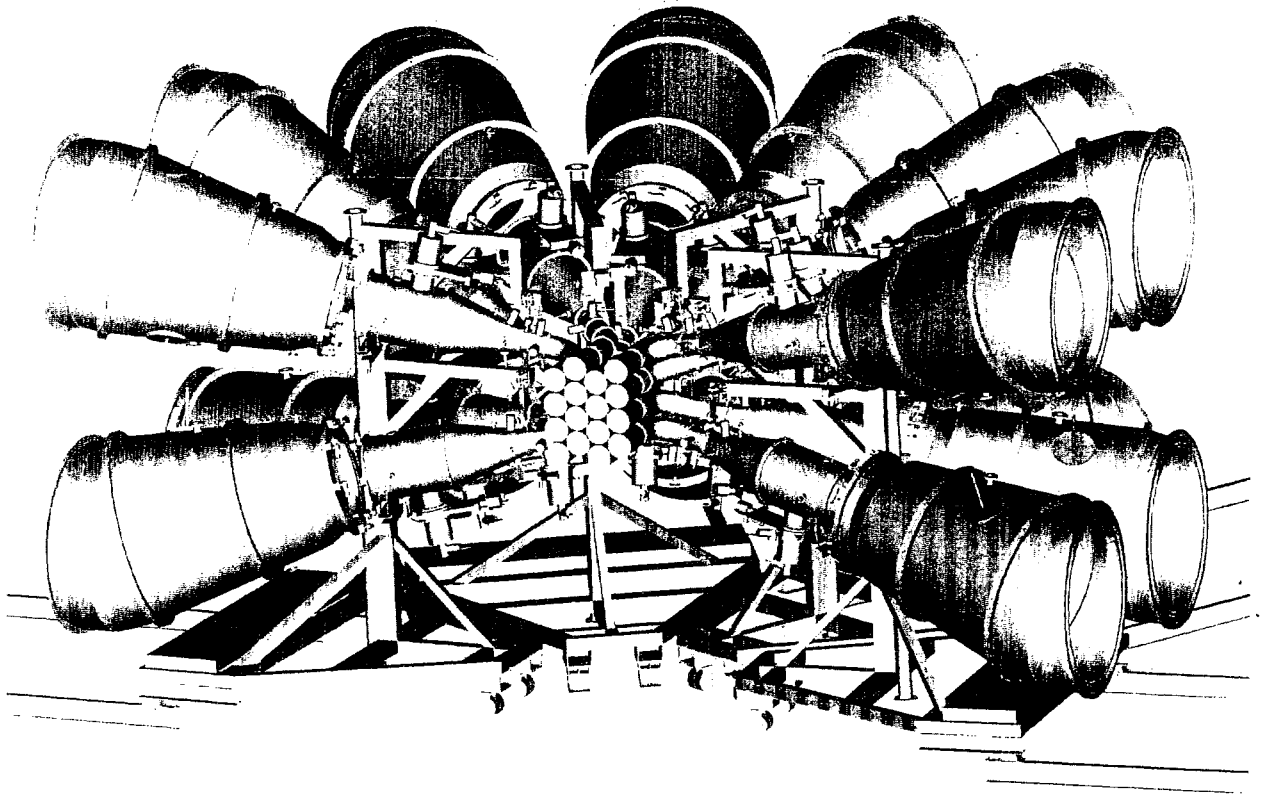


Figure 9. An artists rendering of the DECADE Simulator.

OL, the MITL section and the sixteen hexagonally close packed diode configurations. The MITL is shown disconnected from the tube section of the machine. The radiation output from the machine provides a uniform (2 to 1 peak to valley), approximately  $10,000 \text{ cm}^2$  test area 5 inches from the plane of the diodes. Notice each of the modules is operated independently from the Marx through the diode and can be fired separately or as the 16 module ensemble.



**Figure 10. Isometric view of the DECADE front-end.**

The combination of the radiation output from the individual modules into a single composite 40 ns (FWHM) radiation pulse at the testing plane requires; low total timing jitter ( $\leq 10$  ns command fire to peak x-ray power), a narrow 35 ns FWHM single module pulse width and a method of adjusting timing differences between modules.

The x-ray power measured on a run of sixteen shots on DM1 are shown in Figure 11(a). The sixteen waveforms are shown overlaid as referenced to the initiation ( $t = 0$ ) of the command fire sequence. This is a method of simulating the expected radiation pulse shape from the sixteen module system with one module. Adding up all of these sixteen radiation waveforms produces the predicted composite DECADE radiation pulse shape as shown in Figure 11(b). Note the FWHM of the predicted radiated power on DECADE is 40 ns.

Another key system issue is the ability to replace the POS plasma gun sources and maintain the same module timing (no change in conduction time). Tests on DM1 have been completed to assess the impact of replacing the POS guns. The test results are shown in Figure 12. This plot shows the total time to x-ray output as a function of shot number. The test began with an initial set of POS guns that were replaced on shot 1340. The new set maintained the same timing to x-rays. At the end of the run a third set of POS guns

was installed and also maintained the x-ray timing. The timing jitter on these 28 shots was  $\pm 8$  ns which is less than the required  $\pm 10$  ns.

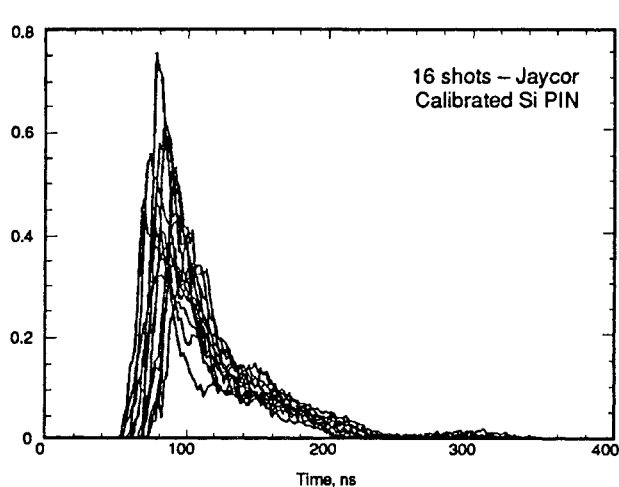


Figure 11(a) X-ray power on 16 DM1 shots

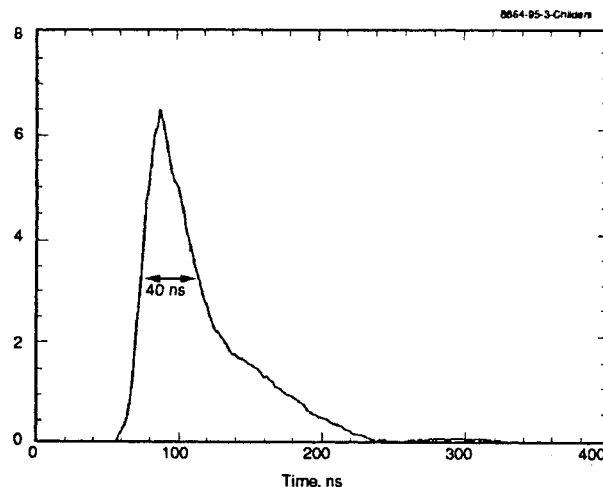
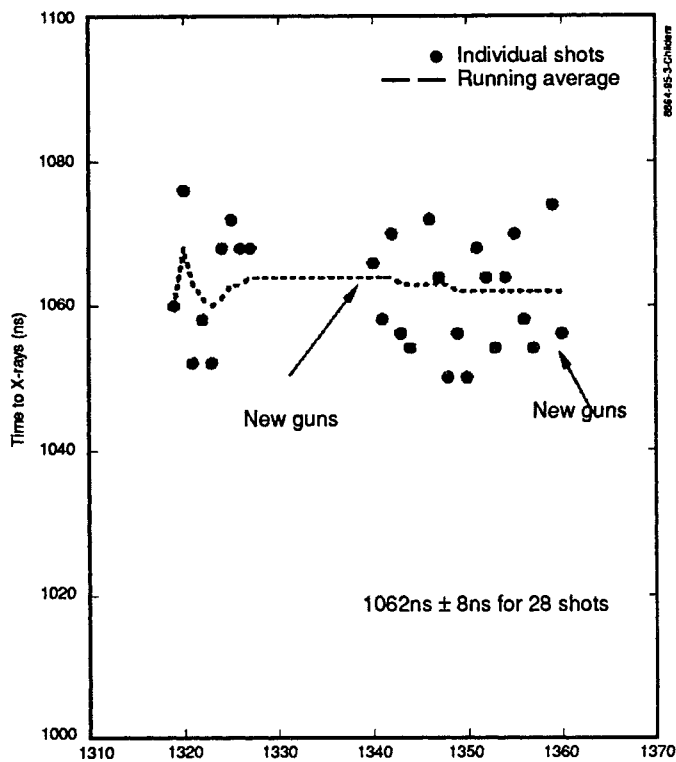


Figure 11(b) Addition of the pulses in (a) provides the projected DECADE composite X-ray pulse shape

**Figure 11.** The measured X-ray power shape on 16 DM1 shots is used to predict the X-ray power pulsewidth on DECADE.



**Figure 12.** This data set demonstrates the ability to maintain the total time to X-ray output after replacing the POS plasma guns.

The last critical timing issue for the DECADE system is the ability to adjust timing differences among the individual modules. This timing difference should be small ( $< 20$  ns) since the Marx capacitance and Marx charge voltage will be carefully controlled among the modules. The DECADE system design includes two methods of adjusting the individual module's time to x-rays. First each module on DECADE has a separate command fire timing control on the TC output switches. The capability to adjust module timing over a 100 ns range has been demonstrated on DM1 as shown in Figure 13(a). The second method of timing control is to adjust the POS conduction time by changing the plasma density of the conducting plasma. The electrical parameter that is adjusted to change the POS plasma density is the POS plasma gun charge voltage. Each of the modules on DECADE will have a separate computer controlled voltage power supply for the POS guns. The capability to adjust the module timing over a 30 ns range by this method was demonstrated on DM1 as shown in Figure 13(b). Either method can be used to eliminate the projected timing differences between modules on DECADE. The reason for providing both methods is that the peak power from individual modules may be optimized at different conduction times in which case the TC timing control would be used to eliminate timing differences.

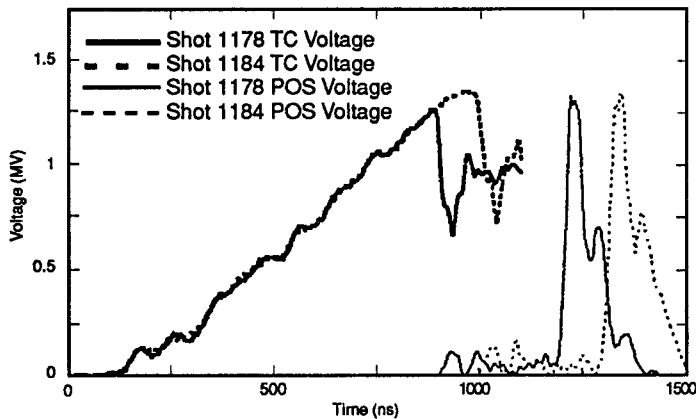


Figure 13(a) Method 1, absolute time of opening can be controlled through output switch timing

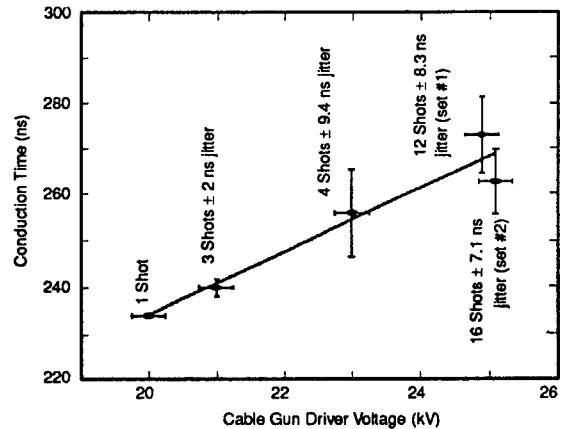


Figure 13(b) Method 2, conduction time can be controlled through the POS plasma power supply

Figure 13. There are two methods for adjusting the timing differences between the modules on DECADE.

## Conclusions/Future Work

A full power unit module of the DECADE simulator has been built and tested for over 1,500 shots. This is the first large simulator built in the US using inductive store/opening switch technology for the final stage of pulse compression.

The electrical performance of the new machine is well understood up to the POS and an accurate computer model of the machine has been developed. The machine has been operating reliably at full Marx charge and has demonstrated the required maintenance cycles for DECADE.

The DECADE system design has been completed. The critical issue of combining sixteen individual radiation pulses into a single composite DECADE pulse has been successfully demonstrated on DM1. The standard deviation in the x-ray timing is  $\pm 8$  ns that results in a 40 ns composite DECADE pulse width.

The work on DM1 is presently focused on measuring the current and voltage in the diode load and completing the model development to include the load. Initial radiation dose measurements suggest the electron current delivered to the tantalum anode is a factor of two below the projected machine capability. Plans for

improved diagnostics between the POS and the load are in progress. These improved diagnostics will facilitate the final engineering development of the POS and diode load combination.

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